ENHANCE MINING SYSTEM RELIABILITY THROUGH SYSTEM INTEGRATION APPROACH

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ABSTRACT

The reliability of mining systems is generally low due to their harsh working conditions. Currently, efforts for improving mining system reliability are often made in isolation. This practice could substantially limit the effectiveness of the efforts on overall reliability improvement of the mining system. To enhance the overall reliability of mining systems, an integrated improvement approach is necessary. In this paper, we developed a framework for integrated mining system reliability improvement to address this issue. In this framework, there are five major components including data integration, business process integration, hardware integration, software integration, and analysis/decision integration, but we only focus on the integrated reliability analysis which is important to the analysis/decision integration. The reliability analysis considers the interactions between machines, and the impacts of design, operation, maintenance, automation and working environment on the overall system reliability. These multiple interactions present a big challenge to accurate reliability prediction. In this paper, we for the first time systematically investigated integrated reliability analysis approaches for dealing with this challenge using novel models and methods, including covariate hazard models, intelligent reliability prediction approach, and complex system modeling methods. While these models and methods have found some successful applications in other industries, they in general have not been effectively used for the reliability analysis of mining systems. Our study results show that the system integration approach is applicable to mining systems and can be used for developing a computer aided integration system for the implementation of the integrated reliability improvement approach.

KEYWORDS

Reliability, mining system, integration, failure rate, safety, productivity

INTRODUCTION

Currently, the availability of mining systems, which consist of various machines, equipment and tools, is still very low compared with those engineering systems used in other industries. Two major reasons accounting for this low availability are (1) the harsh working condition in mine sites and (2) the complexity of mining systems. On the one hand, the reliability of a complex mining system with a large number of subsystems and components, which often have high failure rates due to the harsh working conditions, is normally low because any failure of its critical subsystems or components, if there is not redundancy, will cause the entire system to shut down. For example, according to Hoseinie, Ataei, Khalokakaie, Ghodrati, and Kumar (2012), the reliability of a longwall shearer used in Tabas coalmine, Iran was only 0.5 over the first 12 hours of operation. On the other hand, once a mining system has a failure, it needs much longer time to be fixed because of the harsh environment. Increasing the reliability of mining systems is important to mines because economical loss due to mining system shutdown, especially unplanned shutdown can be huge. As only a functional mining system, rather than any of its subsystems, can produce coal or other minerals, improving the overall reliability of mining systems is crucial to the improvement of mining performance including safety and productivity.

Studies on the reliability of mining machines, equipment or systems have attracted a great attention of academic researchers and industrial practitioners. In 1992, Deillon and Anudr reviewed 197 publications relating to research on the mining equipment reliability across 44 sources from 1965 to 1989. Their research showed that the publications on mining equipment reliability over this period had increased exponentially. From the brief literature review presented by Hoseinie et al. in 2012, it can be seen that the reliability of mining systems was still of great concern after 1992. While most research focused on some specific aspects of mining system engineering such as failure prediction (Vayenas & Yurly, 2007; Samanta & Sarkar, 2012), or reliability assessment for specific machines or systems, e.g., load haul dumper (Samanta, Sarkar, & Mukherjee 2004), longwall shearer (Hoseinie et al., 2012) and crushing plant (Barabady & Kumar, 2008), Kargl, Gimpel, Haubmann, and Preimesberger (2011) indicated that integration of features such as positioning support, automation of cutting sequence, condition monitoring and diagnosis, and maintenance planning was a focus of technical improvement of face mining systems although the integration was not the focus of the article.

A lot of effort has been made to improve the reliability of mining machines and equipment from different aspects such as design, operation, maintenance and automation. A major problem in the current practice is that the improvement efforts in different aspects are often made in isolation. This practice can substantially limit the effectiveness of the efforts on the reliability improvement of overall mining system. For example, innovation in mining machine automation is currently a hot topic of the research because it can significantly improve operational safety and production efficiency of mining machines. Automation will allow operators to operate mining machines remotely. As a result, those machine abnormal conditions that can be observed by operators near the machines may no longer be identified in time and risk of sudden failures could increase. To reduce the risk, new condition monitoring strategies and maintenance strategies are often needed. On the other hand, a lot of data collected through automation system can be valuable for machine condition assessment and maintenance decision-making. If the automation system is not integrated with asset management system in an effective way, the valuable information in these data may not be utilised. Therefore, an integrated improvement approach is really necessary for enhancing the overall reliability of mining machines and equipment.

System integration approach is not a new idea. It has been successfully applied to develop integrated engineering asset management system (Sun, Ma, Zhang, & Zhang, 2008; Mathew, 2008), but new integration approach is needed for improving mining system reliability in an effective manner because mining industry has its own requirements and characteristics. To address this issue, we attempt to develop an integration framework for integrated reliability improvement of mining system. Given that reliability analysis is one of the core functions in this framework, the integrated reliability assessment and prediction will be discussed in more details. The reliability analysis has to consider the interactions between machines, as well as the impacts of design, operation, maintenance, automation, and working environment on the overall system reliability. These multiple interactions present a big challenge for accurate reliability prediction and optimal decision making. The novel models and methods for dealing with the challenge, including covariate hazard models (Sun, Ma, Mathew, Wang, & Zhang, 2006; Louit, Pascual, Banjevic, & Jardine, 2011), Split System Approach (SSA; Sun, Ma, & Morris, 2009), intelligent reliability prediction approach (Yu, Ma, Sun, & Gu, 2010), and complex system modeling method, will be investigated. While these models and methods have found some successful applications in other industries, in general they have not been effectively used for the reliability analysis of mining system. In this paper, we will demonstrate how they can be used in the mining industry. We will also systematically investigate approaches for integrated reliability analysis.

SYSTEM INTEGRATION FRAMEWORK

Numerous factors can affect the reliability of a mining system, including design, manufacturing, operation, and maintenance. Besides, automation, condition monitoring, asset management business processes, as well as interactions between subsystems such as machines and equipment in the system can also affect the reliability of the system. The integrated reliability improvement approach means that all critical factors and their interactions which can affect mining system reliability should be considered in a systematic way so that all the related activities can be integrated towards the improvement of the overall reliability of the entire mining system. Figure 1 shows an integration framework proposed for achieving this purpose. This framework consists of five core components including data integration, business process integration, hardware integration, software integration, and analysis/decision integration.

Data integration requires different types of data from various resources to be integrated for making system reliability improvement decisions in a holistic view. The data include not only those that affect reliability analysis such as machine age, historical failure, maintenance history, condition monitoring data, and machine working environment, but also constraints which affect improvement actions such as financial data, policies and legislations, logistics, customer needs, and environmental requirements. An optimal decision is to maximize system overall reliability with minimum cost within the constraints. Because data collection and storage are often time-consuming and costly, identifying right data requirements is important. An effective way is to analyze data requirements based on decision objectives (Sun, Fidge, & Ma, 2012).

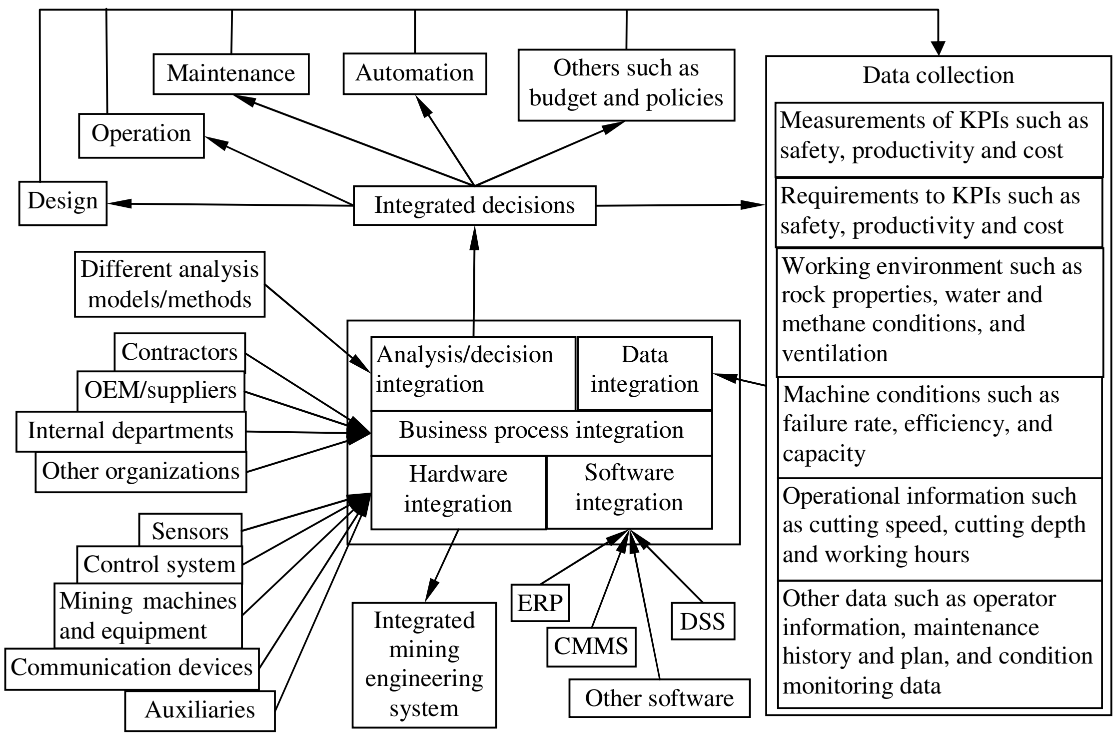
Analysis/decision integration includes (1) the integration of various analysis models and approaches to increase analysis accuracy and decision confidence level; and (2) making decisions in a holistic view. This integration often enables some model selections and analyses to be automatically or semi-automatically conducted. Some contents in this element will be further discussed in the next section.

Process integration requires an integration of those business processes that affect reliability improvement. These processes not only include those within a mine, but often involve some processes across different departments in a mining company and used by the organizations outside the company such as OEM and contractors. Process integration is important as it can often significantly accelerate maintenance responses to prevent catastrophic failures and shorten repair time. An example of improving transformers after-sale maintenance service is given in (Trappey, Sun, Trappey, & Ma, 2011).

Software integration is for supporting the data integration, process integration, and analysis/decision integration. It requires that software packages which contain the required data for reliability analysis and decision making be integrated. A mining company often has various software programs in use. It is often not economical, if not impossible, to develop or use a new software package to replace all existing software programs. A better solution would be developing a software system which can obtain the required data from and export analysis results to the existing programs.

Hardware integration requires that all equipment, machines, devices and infrastructure used in mining system be integrated for improving the overall system reliability and efficiency. These machines, equipment, sensors and other physical structures often interact with each other. Hardware integration can reduce unnecessary devices and components, and hence increase overall system reliability.

The realization of the above integrations needs various technologies and innovations, but in this paper we only discuss approaches to integrated reliability analysis briefly.



OEM – Original Equipment Manufacturer
KPIs – Key performance indicators

ERP – Enterprise Resource Planning
DSS – Decision Support System
CMMS – Computerized Maintenance Management System

Figure 1 – An integration framework for integrated mining system reliability improvement

INTEGRATED RELIABILITY ANALYSIS APPROACHES

A huge number of models and methods have been developed for reliability analysis. These models often have different assumptions and limitations. To enhance the capability of these models, increase analysis accuracy, and automate some analyses, the following integration approaches can be used: (1) consolidation of models with same outputs and different inputs; (2)

integration of models with same outputs and similar inputs; (3) combination of models in sequential relations; and (4) application of complex system modeling techniques.

Consolidation of Models with Same Outputs and Different Inputs

In this approach, the models that have the same output variables but require different input data/information are consolidated. This approach enables available data to be fully used. For example, both Proportional Hazard Model (PHM) [Louit, et al., 2011] and Proportional Covariate Model (PCM) [Sun, et al., 2006] are covariate models which can update the prediction of system hazard (used to describe the conditional probability of failure of a system in reliability engineering) using condition monitoring data (called covariates in reliability engineering). PHM has the following form:

$$h(t) = h_0(t)\psi(t) \tag{1}$$

where $h(t)$ is the hazard function of a system, $h_0(t)$ is the baseline hazard function of the system, and $\psi(t)$ is a function of covariates. Eq. (1) indicates that the hazard of a system changes when its covariates change. Therefore, it is more suitable for the scenarios where the factors that influence system hazard, e.g., working load, cutting speed, lubrication, and dust, have been measured. These factors are often called environmental covariates.

On the other hand, PCM is expressed as:

$$Z(t) = C(t)h(t) \tag{2}$$

Where $Z(t)$ is a function of covariates and $C(t)$ is the baseline covariate function which describes the relationship between the covariates and the hazard of a system. Eq. (2) means that the covariates of a system change when the health condition of the system changes. Therefore, it is more suitable for the scenarios where condition indicators that reflect the health conditions of the system are monitored. These condition indicators, typically including vibration, noise, temperature, and efficiency, are usually called responsive covariates.

Once the hazard function of a system is known, its reliability function, $R(t)$, can be calculated by

$$R(t) = \exp(-\int_0^t h(\tau)d\tau). \tag{3}$$

The integration of PHM and PCM can help mines make better decisions for improving reliability. For example, two identical longwall shearers normally have the same hazard baseline function, but their actual hazards could be different if they are being used under different working conditions. PHM can be used to model the influence of working conditions on the reliability characteristics of the shearers to determine optimum operational parameters. On the other hand, condition monitoring data collected from the shearers can reveal the actual hazards of the machines. PCM can then be used to check if the selected reliability improvement means is really effective based on the condition monitoring data.

Integration of Models with Same Outputs and Similar Inputs

In this approach, the models that have the same output variables and use similar data/information are integrated. This approach can be used to increase the analysis confidence level. For example, if the failure history and condition monitoring data of a mining machine is known, the hazard of the machine can be modeled by some covariate models such as PHM and PCM. It can also be modeled using some artificial intelligent approaches such as Neural Network [Yu, et al., 2010]. The results given by two different methods can be cross-checked or consolidated to increase the prediction confidence level.

Combination of Models in Sequential Relations

If the outcomes of some models can provide inputs to another model, all of these models should be combined. This approach can help enhance the capability of the models and automate the analysis. For example, SSA was developed to predict the reliability of a complex system with multiple imperfect preventive maintenance cycles. It can be used to decide which preventive maintenance strategy is most effective in terms of reliability improvement and cost reduction. It is good for long-term reliability improvement planning of large mining systems. This approach needs inputs from other models for predicting the reliability of a system before any repairs and the reliability functions of planned repaired components. Since the prediction is made based on historical data while the future working conditions of the system may be different from that when these data were collected, it is hard to make accurate long-term predictions. Combination of SSA, PHM and PCM can help update the reliability prediction based on the latest condition information and hence make better reliability improvement decisions.

Application of Complex System Modeling Techniques

This approach indicates that using advanced complex system modeling techniques (CSMT) to help decision makers analyze complex interactions and identify critical factors. As shown in Figure 1, reliability can be improved from various interrelated aspects. Reliability improvement decisions should consider all these aspects in a holistic way to maximize the improvement effectiveness. It is often difficult for a decision maker to finish this task. CSMT such as multi-agent system, fuzzy logic and Bayesian Network (BN) could provide help. For example, the well-established BN has unique advantages when modeling causal relationships. It thus is a good candidate for the reliability analysis and prediction of the complex mining systems. Figure 2 shows a preliminary BN model for drum reliability analysis of continuous miners.

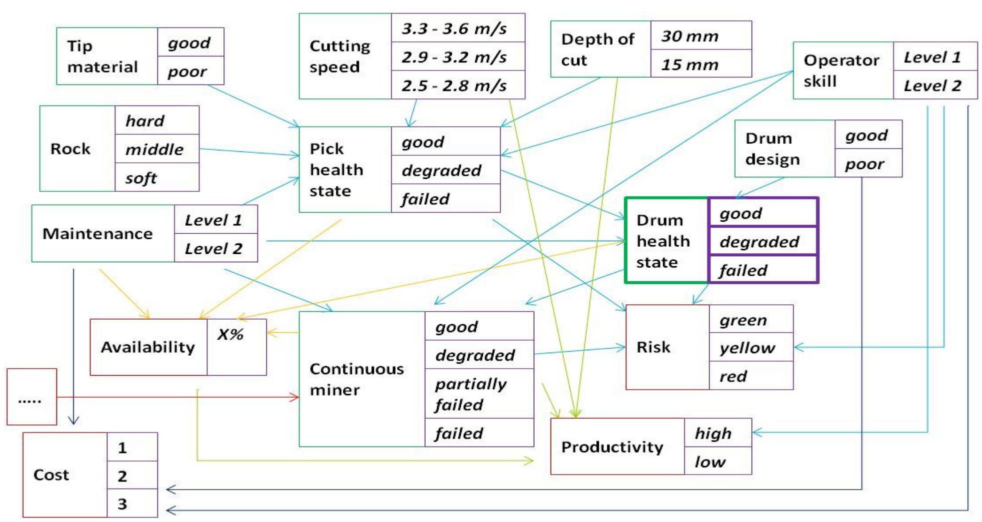


Figure 2 - BN model for drum reliability analysis of continuous miners

In Figure 2, each block represents a random variable. The left side of each block is the name of a variable and the right side is its possible status or value. Note that these blocks are usually called nodes and described using ovals without showing statuses or values. The statuses and values in this figure are assumed for illustrative purpose because they are normally organization dependent. From this figure, it can be seen that the drum's health condition is mainly affected by drum design, maintenance, and pick health condition which is in turn influenced by operator skills, rock conditions, tip material, cutting speed, the depth of cut, and maintenance. On the other hand, because the drum is a part of a continuous miner, its reliability directly affects the overall reliability of the continuous miner which directly influences the availability, productivity and failure risk of the entire mining system. Given the required inputs, the BN model can calculate the probability of a drum in three states and identify the critical factors for its reliability improvement. Moreover, this BN model can be expanded to analyze reliability at any higher levels of a mining system, e.g., the reliability of a continuous miner.

CONCLUSIONS

Most of the mining subsystems are interconnected in series, and hence a mining system can work only when all of its subsystems function properly. Therefore, it is important to improve the overall reliability of the entire mining system. This goal can be effectively achieved only via an integrated improvement approach including data integration, business process integration, hardware integration, software integration, and analysis/decision integration. A critical element in the analysis/decision integration is integrated reliability analysis which can enhance the capability of existing models and automate some reliability analysis. Four technical approaches for the integrated reliability analysis have been presented in the paper.

The integrated reliability improvement often involves a large number of different analyses and normally needs to be implemented with the aid of computer systems. The integration framework and technical approaches presented in this paper can be used for developing a computer aided integration system. Although the study in this paper has demonstrated that the integrated reliability improvement approach is applicable to mining systems, intensive studies based on actual large mining systems are yet to carry out. In addition, as a complete integration system is often complex and takes time to build up, a mine should take a gradual implementation and continuous improvement approach, which will be addressed in our future follow-up publications.

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